

On the Origin of Rapid Flares in TeV Blazars

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ABSTRACT

The rapid variability of the VHE emission reported for some TeV blazars implies Doppler factors well in excess of those inferred from superluminal motions and unification schemes. We propose that those extreme flares may result from radiative deceleration of blobs on scales where local dissipation occurs. The minimum jet power estimated from the resolved synchrotron emission on VLBI scales appears to be consistent with this model. It is shown that if the energy distribution of nonthermal electrons accelerated locally in the blob is reasonably flat, then a background radiation field having a luminosity in the range 10^{41} - 10^{42} erg s⁻¹ can give rise to a substantial deceleration of the blob, but still be transparent enough to allow the TeV γ -rays thereby produced to escape the system.

Subject headings: galaxies: active - quasars: general - radiation mechanism: nonthermal - X-rays:galaxies

1. Introduction

Very high energy emission (VHE, $E \gtrsim 100$ GeV) has been detected from over a dozen blazars (for an updated list see, e.g., Wagner 2007), all of which are exclusively associated with the class of high peak BL Lac objects. The observed bolometric luminosity during quiescent states is typically of the order of a few times 10^{44} ergs s⁻¹, with about 10 percents emitted as VHE γ -rays. The luminosity in the VHE band may be larger by a factor of 10 to 100 during flaring states. The intrinsic spectra (corrected for absorption on the extragalactic background light) appear to be rather steep, but seem to harden with increasing flux. A peak photon energy in excess of 10 TeV has been measured in the most extreme cases. Deviations from a power law are clearly seen in the data in some cases (e.g., Albert et al. 2007).

Rapid variability is a characteristic property of VHE blazars. Large amplitude variations of the VHE γ -ray flux on time scales of several hours and less have been reported

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for Mrk 421, Mrk 501 and PKS 2155-304. This rapid variability implies that the emission at the observed energy originated from a region of size (as measured in the Lab frame) $\Delta r \lesssim 10^{14} \Gamma D t_{\text{var,h}} / (1 + z)$ cm, where Γ and D are the bulk Lorentz factor and the corresponding Doppler factor of the emitting matter, respectively, $t_{\text{var,h}}$ is the observed variability time in hours, and z is the redshift of the source. If the emission originated from small jet radii, $r_{\text{em}} \sim \Delta r$, then the requirement that the γ rays will not be absorbed by pair production on local synchrotron photons implies high Doppler factors, $D \sim 30 - 100$ (Krawczynski 2002; Levinson 2006; Begelman et al. 2007). Such high values are consistent with those obtained from fits of the SED to a homogeneous SSC model¹, but are in clear disagreement with the much lower values inferred from unification schemes (Urry & Padovani 1991; Hardcastle et al. 2003) and superluminal motions on parsec scales (Marscher 1999; Jorstad et al. 2001; Giroletti et al. 2004). Various explanations, including a structure consisting of interacting spine and sheath (Ghisellini et al. 2005), opening angle effects (Gopal-Krishna et al. 2004) and jet deceleration (Georganopoulos & Kazanaz 2003; Piner & Edwards 2005) have been proposed in order to resolve this discrepancy. A variant of the decelerating jet model is considered further below.

It has been argued that such high values of the Doppler factor may not be required if the γ -ray production zone is located far from the black hole, at radii $r_{\text{em}} \gg \Delta r$. In that case the compactness of the TeV emission zone may be constrained by the variability of the IR flux observed simultaneously with the TeV flare, allowing low values of D in cases where the variability time of the IR emission is much longer than the duration of the TeV flare. However, the fraction of jet energy that can be tapped for production of γ rays in a region of size Δr located at a radius r_{em} is $\eta \sim (\Delta r / \theta r_{\text{em}})^2$. As a consequence, either the opening angle of the jet must be very small, $\theta \sim \Delta r / r_{\text{em}} \ll 1$, or the jet power must be much larger than the luminosity of the TeV emission measured during the flare. Another possibility is that the TeV emission is produced by a converging shock in a reconfinement nozzle, as proposed for the HST1 knot in M87 (Cheung et al. 2007). It should be noted though that in M87 the X-ray and TeV luminosities, $L_{\text{TeV}} \sim L_{\text{x}} \lesssim 10^{41}$ erg s⁻¹ (Aharonian et al. 2006; Cheung et al. 2007), are much smaller than the TeV luminosity, $L_{\text{TeV}} \sim 10^{44-45}$ erg s⁻¹, observed typically in the TeV blazars. Estimates of the jet power in M87 yield $L_j \gtrsim 10^{44}$ erg s⁻¹ (e.g., Bicknell & Begelman 1996; Stawarz et al. 2006), implying a very small conversion fraction, $L_{\text{TeV}} / L_j \lesssim 10^{-3}$. Even with such a small conversion efficiency an opening angle $\theta < 10^{-2}$ rad is required if the TeV emission were to originate from the HST1 knot, unless reconfinement can give rise to sufficient convergence of the jet at the location of HST1, as proposed by (Cheung et al. 2007). We note that even modest radiative cooling of the

¹Compactness would constrain the location of the TeV emission region in this model

shocked jet layer in a proton dominated jet will lead to such a convergence, at least in the non-relativistic case (Peter & Eichler 1995). The effect of cooling on the collimation of relativistic jets needs to be explored, but we expect a similar behavior. Stationary radio features observed on VLBI scales (e.g., Jorstad et al. 2001) seem to indicate that recollimation shocks may be an important dissipation channel in blazars, and this may apply also to other sources, e.g., GRBs (Bromberg & Levinson 2007). Whether the extreme TeV flares observed in VHE blazars can be accounted for by recollimation shocks at radii $r_{\text{em}} \gg \Delta r$ remains to be explored. As stated above, this would not resolve the ‘Doppler factor crises’ if the IR emission will turn out to vary on timescales comparable to the TeV emission.

(Georganopoulos & Kazanaz 2003, GK03) proposed a scenario in which the deceleration of the fast jet base is mediated by Compton scattering of synchrotron photons produced further downstream, in the slow part of the flow. The major fraction of the bulk energy is assumed to be converted to TeV radiation within the transition layer, so there is no missing energy problem in this model. The main motivation in that paper was to reproduce the observed SED in a source that propagates at mildly relativistic speeds on VLBI scales. Using a given bulk velocity profile for the decelerating plasma GK03 computed the spectrum emitted from the jet and argued that deceleration from a modest Lorentz factor ($\Gamma \sim 15$) down to $\Gamma \sim$ a few in a jet observed at sufficiently small viewing angles ($\theta_n \lesssim 3^\circ$) can indeed account for the average SED observed in TeV blazars. The dynamics of the system has not been treated in a self-consistent manner in GK03. In particular, it has not been demonstrated that (i) the backward emission from the slow jet section can provide sufficient radiative drag to decelerate the fast jet, and (ii) that the TeV photons can escape to infinity. Moreover, as explained above the Doppler factors inferred from opacity constraints during the extreme flaring states observed in Mrk 412, Mrk 501 and Pks 2155-304 are considerably larger than those invoked in GK03 to explain the average broad-band spectrum of these sources.

In this paper we consider the possibility that those extreme flares are produced by radiative deceleration of fluid shells on scales where local dissipation occurs ($r_d \sim 10^2 - 10^3 r_g$). The dissipation may be accomplished through formation of internal shocks in a hydrodynamic jet or dissipation of magnetic energy in a Poynting flux dominated jet. A similar model has been proposed earlier for flares in EGRET blazars (Romanova & Lovelace 1992; Levinson 1998). For the TeV blazars a background luminosity $L_s \sim 10^{41} - 10^{42} \text{ erg s}^{-1}$ would lead to a substantial deceleration of the front and still be transparent enough to allow the TeV γ -rays produced by Compton scattering of the background photons to escape the system, provided the energy distribution of radiating electrons is sufficiently flat. The ambient radiation field is most likely associated with the nuclear continuum source. The bulk Lorentz factor of the jet during states of low activity may be appreciably smaller than that of fronts expelled

during violent ejection episodes.

2. Minimum Jet Power: A Consistency Check

The decelerating jet scenario implies that the major fraction of the bulk energy is radiated away in the form of VHE photons on very small scales ($\sim 10^2 - 10^3 r_g$). Consequently, the remaining jet power on VLBI scales must be much smaller than the luminosity of the VHE γ -ray emission. As a consistency check, we estimate the minimum power of the pc scale radio jet. From the resolved radio synchrotron emission emitted at a radius $r = 1 r_{pc}$ pc from a jet of opening angle $\theta = 0.1 \theta_{-1}$ rad we define a fiducial equipartition magnetic field strength $B^* \sim 5(T_{B9}/\theta_{-1} r_{pc})^{2/7} \nu_9^{5/7}$ mG, where the brightness temperature $T_B = 10^9 T_{B9}$ K is evaluated at the observed frequency $\nu = \nu_9$ GHz, and the radio spectral index is $\alpha_R \sim 0.5$ (cf., Rybicki & Lightman 1979). Let the jet Lorentz factor be Γ and let its velocity makes an angle θ_n with the line of sight. The jet power associated with the emitting electrons and the electromagnetic field is then given by

$$L_j \geq \frac{c}{2} \left(\frac{\Gamma B^* \theta r}{D^{5/7}} \right)^2 \sim 10^{40} \left(\frac{\theta_{-1} r_{pc}}{D} \right)^{10/7} \Gamma^2 T_{B9}^{4/7} \nu_9^{5/7} \quad \text{erg s}^{-1} \quad (1)$$

where $D = [\Gamma(1 - \beta \cos \theta_n)]^{-1}$ is the Doppler factor and rough equality occurs at equipartition.

VLBA images of Mrk 421 at 15 and 22 GHz reveal a core jet morphology (Marscher 1999), with some jet components at a linear distance of $r_{pc} \sim 1$ from the core. The jet components contain only a few percents of the total flux density (of the order of 1 Jy). The resolution at 15 GHz is about 0.5 mas. From the above we estimate $T_{B9}(\nu = 15 \text{ GHz}) \lesssim 1$ for the jet, and a minimum power of $L_{j,\min} \sim 10^{41}$ erg s $^{-1}$. For Mrk 501 we obtain similar numbers. Thus, the minimum jet power inferred from the resolved radio emission is well below the TeV luminosity measured in these sources, $L_{\text{TeV}} \gtrsim 10^{44}$ erg s $^{-1}$. This should be contrasted with FRII sources where $T_B \gtrsim 10^{12}$ K are measured (Readhead 1994), implying a minimum jet power close to the Eddington limit, and radio jets in microquasars, where a minimum jet power in excess of the Eddington limit has been measured on scales of $\sim 10^9 r_g$ (Levinson & Blandford 1996; Distefano et al. 2002).

3. Radiative Deceleration of Relativistic Shells

Consider a fluid shell, described by a stress-energy tensor

$$T^{\alpha\beta} = h n u^\alpha u^\beta - p \eta^{\alpha\beta} + \frac{1}{4\pi} (F^{\alpha\sigma} F_\sigma^\beta + \frac{1}{4} \eta^{\alpha\beta} F^2), \quad (2)$$

where $F_{\mu\nu}$ is the electromagnetic tensor, $u^\alpha = (\Gamma, \Gamma\beta)$ is the 4-velocity of the bulk fluid, and n , p , and h , are the proper particle density, pressure and specific enthalpy, respectively, interacting with some ambient radiation field. Suppose that the shell has been ejected and accelerated to a bulk Lorentz factor Γ_0 at some radius $r_d \sim 10^2 r_g$, at which dissipation suddenly commences, e.g., due to collision with another shell or with a confining medium. The dynamics of the front is governed by the energy momentum equations,

$$\frac{\partial}{\partial x^\alpha} T^{\alpha\mu} = S_c^\mu, \quad (3)$$

where the source term S_c^μ accounts for the radiative force acting on the front. In terms of the distribution functions of the target photons, f_s , and electrons (we don't distinguish here between electrons and positrons), f_e , the source term associated with the radiative force is given, in the limit of Thomson scattering, by (Sikora & Wilson 1981; Phinney 1982)

$$S_c^\mu = -c\sigma_T \int \frac{d^3 p_e}{p_e^0} \int \frac{d^3 p_s}{p_s^0} f_s f_e p_{e\alpha} p_s^\alpha \left[p_s^\mu + \frac{(p_{e\nu} p_s^\nu) p_e^\mu}{m_e^2 c^2} \right], \quad (4)$$

with p_e^μ and p_s^μ being the 4 momenta of electrons and soft photons, respectively, as measured in the Lab frame. We suppose that the electron distribution function is isotropic in the fluid rest frame and can be approximated as a power law: $dn'_e/d\gamma = 4\pi m_e c p^2 f_e(p) \propto \gamma^{-q}$; $\gamma_{min} < \gamma < \gamma_{max}$, where $m_e c^2 \gamma$ is the corresponding electron energy, as measured in the comoving frame. We further suppose that the photon distribution is isotropic in the star frame. Under the above assumptions the zeroth component of eq. (4) yields,

$$S_c^0 = -\frac{4}{3} \Gamma^3 < \gamma^2 > u_s \sigma_T n'_e. \quad (5)$$

Here

$$n'_e = \int f_e d^3 p_e = \int_{\gamma_{min}}^{\gamma_{max}} \frac{dn'_e}{d\gamma} d\gamma, \quad (6)$$

is the proper number density of nonthermal electrons,

$$< \gamma^2 > = \frac{1}{n_e} \int \gamma^2 f_e d^3 p_e, \quad (7)$$

and $u_s(r)$ is the total energy density of the target radiation field at radius r . Let $u'_e = \int \gamma m_e c^2 f_e d^3 p_e$ be the proper energy density of nonthermal electrons, $< \gamma > m_e c^2 = u'_e/n_e$ their average energy, and define $< \gamma^2 > / < \gamma > = \chi \gamma_{max}$. In terms of these quantities the radiative force term (eq. [5]) can be re-expressed as

$$S_c^0 = -\frac{4\sigma_T}{3m_e c^2} \chi \Gamma^3 \gamma_{max} u_s u'_e. \quad (8)$$

For the power law energy distribution invoked above we have $\chi = (2 - q)/(3 - q)$ if $q < 2$, $\chi = [\ln(\gamma_{\max}/\gamma_{\min})]^{-1}$ if $q = 2$, and $\chi \simeq (\gamma_{\min}/\gamma_{\max})^{q-2}$ if $q > 2$. With $\gamma_{\min} = m_p/m_e$ and $\gamma_{\max} = 10^6$ we have $\chi > 0.1$ for $q \leq 2$.

The energy flux of the decelerating front can be obtained from eq. (2):

$$T^{0r} = (nh + B'^2/4\pi)\Gamma^2\beta \equiv u'_j\Gamma^2\beta, \quad (9)$$

where n and h are defined above and B' is the rest frame magnetic field. Using eqs. (3), (5) and (9) we arrive at,

$$\frac{d}{dr}(u'_j\Gamma^2\beta) = -\frac{4\sigma_T}{3m_e c^2}\chi\Gamma^3\gamma_{\max}u_s u'_e. \quad (10)$$

For illustration suppose that $u_s(r) \propto r^{-2}$ and that the proper density and average energy of the nonthermal electrons are independent of radius. In the limit $\beta = 1$ the solution to eq. (10) reads

$$\Gamma_\infty = \Gamma_0 \frac{l}{l + r_d}, \quad (11)$$

where $\Gamma_0 = \Gamma(r = r_d)$, and the stopping length l is given by

$$l = \frac{3m_e c^2}{2\sigma_T \chi \xi_e \Gamma_0 \gamma_{\max} u_s(r_d)}. \quad (12)$$

In the last equation $\xi_e = u'_e/u'_j < 1$ denotes the fraction of total jet energy carried by the nonthermal electron population.

In order to calculate the pair production opacity the spectrum of the target radiation field must be specified. For simplicity let us assume a power law spectrum, $I_s(\epsilon_s) \propto \epsilon_s^{-\alpha}$; $\epsilon_{s,\min} < \epsilon_s < \epsilon_{s,\max}$, where $I_s = hcp_s^3 f_s$ is the intensity and $\epsilon_s = p_s/m_e c$ denotes the photon energy in $m_e c^2$ units. The optical depth for absorption of γ rays of dimensionless energy ϵ_γ by pair creation is then given to a good approximation by

$$\tau_{\gamma\gamma}(\epsilon_\gamma) \simeq \sigma_{\gamma\gamma} r_d (u_s/m_e c^2) \epsilon_\gamma g(\epsilon_\gamma), \quad (13)$$

with $g(\epsilon_\gamma) = (\epsilon_\gamma \epsilon_{s,\min})^{\alpha-1}$ if $\alpha > 1$ and $g(\epsilon_\gamma) = (\epsilon_\gamma \epsilon_{s,\max})^{\alpha-1}$ if $\alpha < 1$, and $g(\epsilon_\gamma) \leq 1$ in both cases. Using eqs. (12) and (13), the stopping length can be expressed in terms of the γ -ray optical depth as,

$$\frac{l}{r_d} = \frac{1}{\chi \xi_e \tau_{\gamma\gamma}} \left(\frac{\sigma_{\gamma\gamma}}{\sigma_T} \right) \left(\frac{\epsilon_\gamma}{\Gamma_0 \gamma_{\max}} \right) g(\epsilon_\gamma). \quad (14)$$

Note that since the observed γ -rays are produced by Compton scattering of the front electrons we must have $\Gamma_0 \gamma_{\max} > \epsilon_\gamma$ for any ϵ_γ . The highest γ -ray energy observed is likely to be limited

by opacity. Denoting by $\epsilon_{\gamma,\text{th}}$ the photon energy at which the pair production opacity is unity, viz., $\tau_{\gamma\gamma}(\epsilon_{\gamma,\text{th}}) \simeq 1$, and taking $\sigma_{\gamma\gamma}/\sigma_T = 0.2$ we find that $l/r_d < 1$ if

$$\left(\frac{\Gamma_0 \gamma_{\text{max}}}{\epsilon_{\gamma,\text{th}}} \right) > \frac{g(\epsilon_{\gamma,\text{th}})}{5\chi\xi_e}. \quad (15)$$

Adopting for illustration $\chi = \xi_e = 0.1$, $g(\epsilon_{\gamma,\text{th}}) = 0.1$, we conclude that extension of the nonthermal electron spectrum to a maximum energy γ_{max} of the order of a few times $\epsilon_{\gamma,\text{th}}/\Gamma_0$ is sufficient to cause appreciable deceleration of the front. Gamma rays having energies above $\epsilon_{\gamma,\text{th}}$ will be degraded to somewhat lower energies by virtue of the relatively large pair production opacity. Thus, we naively anticipate some accumulation of flux around the maximum observed γ -ray energy, at \sim a few TeV, although we stress that detailed calculations are required to determine the exact shape of the spectrum. The corresponding luminosity of the ambient radiation can be estimated from eq. (13) to be

$$L_s \simeq \frac{m_e c^3 r_d}{\sigma_{\gamma\gamma} \epsilon_{\gamma,\text{th}} g(\epsilon_{\gamma,\text{th}})} \simeq 10^{40} r_{d16} (\epsilon_{\gamma,\text{th}}/10^7) g^{-1} \quad \text{erg s}^{-1}. \quad (16)$$

Assuming the acceleration rate of nonthermal electrons to be on the order of their gyro-frequency, we estimate $\gamma_{\text{max}} \lesssim 10^{7.5}$ for magnetic field energy density $u'_B \simeq 0.1 u'_j$. For $\Gamma_0 = 30$ this corresponds to $\Gamma_0 \gamma_{\text{max}}/\epsilon_{\gamma} \simeq 50$ for the highest γ -ray energy observed (~ 10 TeV). If the ambient photons originate from a central continuum source (e.g., accretion disk), and about 10 percents are intercepted by the jet, then of the order of $10^{41} - 10^{42}$ erg s $^{-1}$, roughly the luminosity observed in LLAGNs, is required to accommodate the spectrum and variability of the TeV blazars.

We consider now the possibility that the target photons originate from the slow part of the flow (GK03). Assuming for illustration that the proper energy density u'_j remains constant we have $L_{j\infty} = (\Gamma_\infty/\Gamma_0)^2 L_j$. The fraction of synchrotron luminosity emitted backwards (into a solid angle Γ_∞^{-1} in the rest frame of the slow flow), as measured in the Lab frame, is $\sim \Gamma_\infty^{-4}$. Consequently, the luminosity of target photons is at most $\Gamma_\infty^{-4} L_{j\infty}$ or $L_s \lesssim L_j/(\Gamma_\infty \Gamma_0)^2$. Adopting $L_j = 10^{45}$ erg s $^{-1}$, roughly the observed TeV luminosity, and $\Gamma_\infty = 4$, we deduce that Γ_0 cannot be larger than 20 or so in order that L_s will satisfy the requirements imposed in eq. (16). Note also that this photon mediated transition is unstable, so that some additional mechanism is required to maintain the flow at low Γ_∞ downstream.

4. Discussion

The rapid variability of the VHE γ -ray emission reported for some VHE blazars implies Doppler factors $D \gtrsim 30$, much larger than those inferred from superluminal motions and

unification schemes. A plausible mechanism that can generate such flares is radiative deceleration of high Lorentz factor shells. The minimum jet power estimated from the resolved synchrotron emission on VLBI scales is consistent with this model. Deceleration to $\Gamma \sim a$ few can be accomplished if a significant fraction of the shell's bulk energy is carried in the form of nonthermal electrons with a sufficiently flat energy distribution ($dn_e/d\gamma \propto \gamma^{-q}$; $q \leq 2$) that extends up to a maximum energy at which the pair production opacity is of the order of a few or larger. The spectrum emitted during the flare is expected to be hard, with νF_ν peaking roughly at an energy at which the pair production opacity is unity. Deviation from a power at the highest energies are expected, owing to attenuation by pair production and temporal effects. Spectral curvature is indeed observed in some cases (Albert et al. 2007). Correlation between the VHE γ -ray emission and emission in other bands, particularly X-ray, is naively anticipated, although detailed calculations are required to assess exact relations (e.g., time lags and amplitude ratios). Such correlations have been reported for Mrk 421 (Fossati et al. 2004). The properties of VHE flares produced by this mechanism should differ from those predicted for the pair cascade jets in powerful blazars, like 3C279, where propagation from low-to-high γ -ray energies is expected (Blandford & Levinson 1995).

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